

# The Gemini NICI Planet-Finding Campaign

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## ABSTRACT

Our team is carrying out a multi-year observing program to directly image and characterize young extrasolar planets using the Near-Infrared Coronagraphic Imager (NICI) on the Gemini-South 8.1-meter telescope. NICI is the first instrument on a large telescope designed from the outset for high-contrast imaging, comprising a high-performance curvature adaptive optics (AO) system with a simultaneous dual-channel coronagraphic imager. Combined with state-of-the-art AO observing methods and data processing, NICI typically achieves  $\approx 2$  magnitudes better contrast compared to previous ground-based or space-based planet-finding efforts, at separations inside of  $\approx 2''$ . In preparation for the Campaign, we carried out efforts to identify previously unrecognized young stars as targets, to develop a rigorous quantitative method for constructing our observing strategy, and to optimize the combination of angular differential imaging and spectral differential imaging. The Planet-Finding Campaign is in its second year, with first-epoch imaging of 174 stars already obtained out of a total sample of 300 stars. We describe the Campaign's goals, design, target selection, implementation, on-sky performance, and preliminary results. The NICI Planet-Finding Campaign represents the largest and most sensitive imaging survey to date for massive ( $\gtrsim 1 M_{\text{Jup}}$ ) planets around other stars. Upon completion, the Campaign will establish the best measurements to date on the properties of young gas-giant planets at  $\gtrsim 5$ –10 AU separations. Finally, Campaign discoveries will be well-suited to long-term orbital monitoring and detailed spectrophotometric followup with next-generation planet-finding instruments.

**Keywords:** Extrasolar planets; brown dwarfs; high contrast imaging; adaptive optics; near-IR instrumentation.

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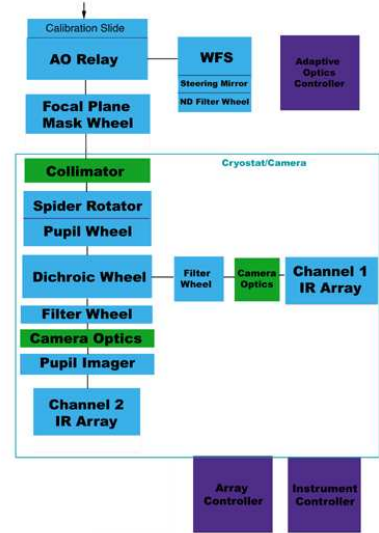


Figure 1. **Left:** NICI at Mauna Kea Infrared in Hilo, Hawaii, prior to acceptance testing. **Right:** Block diagram of NICI optical configuration, including the 85-element curvature AO system, the focal & pupil plane mask mechanisms, and the two IR imaging channels. NICI is the first imager for a 8-10 meter telescope designed expressly for exoplanet imaging and is now in routine operation at the Gemini-South 8.1-meter Telescope.

## 1. INTRODUCTION

Radial velocity (RV) and transit detections of extrasolar planets have been a watershed for observational studies of planet formation, compiling a sample of planets large enough ( $\gtrsim 400$  to date) for statistical studies. However, these discoveries provide an incomplete picture of the extrasolar planet population: most RV planets are detected only indirectly and with the  $\sin i$  ambiguity in their masses, and transiting planets are mostly restricted to very small orbital separations. Direct imaging of exoplanets can measure colors, luminosities and spectra, thereby providing temperatures and compositions. Furthermore, since RV and transit studies are confined to the inner regions of other solar systems ( $< 6$  AU for 15-yr survey), we know very little about the planetary constituents in the outer regions of other solar systems, where gas-giant planets are born.

The discovery of extrasolar planets by direct imaging (1–4) has opened the door to a whole new realm of observational study. Analogous to the growth of RV and transit studies, the next steps in the field of direct imaging will be to move from individual “headline” discoveries to well-defined, well-studied samples to glean the properties of the whole population. Moreover, detailed photometric and spectroscopic analysis of new exoplanet discoveries will allow us to dissect the atmospheric properties and thermal evolution of these objects (e.g., 5–7).

## 2. THE INSTRUMENT

In principle, the largest (8–10 meter) ground-based telescopes equipped with adaptive optics (AO) could be effective for direct imaging of planets, as these platforms achieve the highest possible angular resolution in the near-IR with a filled aperture telescope. However, traditional AO imaging is hampered by the time-variable nature of the point spread function (PSF) and the presense of quasi-static point-like speckles in the images. Thus while AO greatly enhances the contrast (i.e., the ability to detect faint sources next to bright ones), its imperfect correction is a severe limitation to push to planetary masses and separations. This challenge can be overcome with specialized instrumentation.

The Near-Infrared Coronagraphic Imager (NICI) is a powerful AO instrument tailored to direct detection of extrasolar planets through high contrast imaging (**Figure 1**). It is the first instrument on an 8-10 meter telescope designed expressly for such work. NICI was built by Mauna Kea Infrared in Hilo, Hawaii (PI Doug Toomey) and funded by NASA. The instrument is now fully operational at the Gemini-South 8.1-meter telescope.<sup>8</sup> NICI combines a suite of capabilities to achieve high contrast imaging: (1) an efficient natural guide star curvature AO

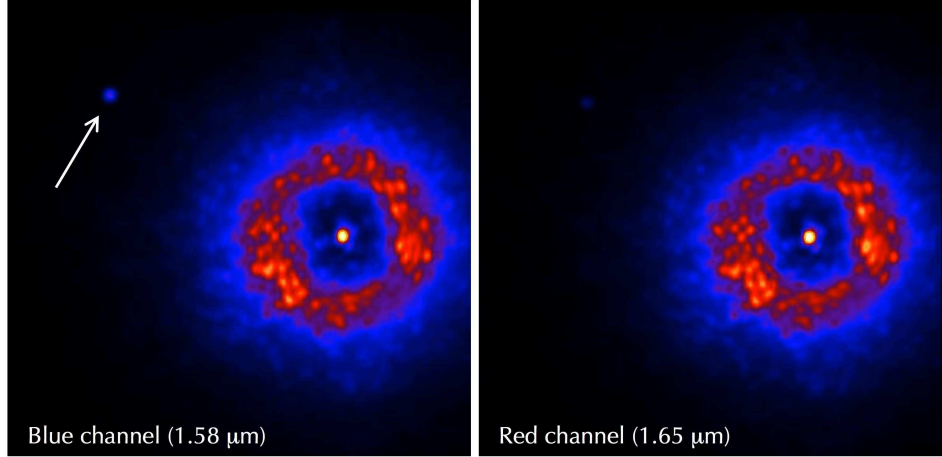


Figure 2. An example of NICI two-channel imaging data from a 1-minute exposure of a bright star. The FOV of each image is  $3.6''$  on a side. The science target is centered on the translucent focal plane mask, and the highly speckled nature of the PSF halo is seen in the images from both channels. An artificial methane-bearing companion has been inserted into the data in the upper left of each image; it is brighter in the left image than the right one due to the presence of methane absorption in the red channel filter.

system built by the University of Hawaii, (2) spectral differential imaging (SDI); (3) angular differential imaging (ADI); and (4) Lyot-style coronagraphy. While these techniques have been used in previous instruments, NICI is the first to bring all of them together into a single instrument.

NICI was designed as a complete end-to-end system for high-contrast imaging, minimizing both the wavefront phase distortions from the atmosphere, telescope and instrument as well as the internal instrumental scatter. NICI first creates a high Strehl image ( $\approx 30\text{--}45\%$  at  $H$ -band) with its own internal low-scatter 85-element curvature AO system. Its wavefront sensor is tailored to the range of natural guide star brightnesses needed for the Planet-Finding Campaign ( $V \lesssim 14$  mag). Unlike most other AO systems to date, the corrected AO beam is reflected into the science channel and the first transmissive element is the focal-plane mask. The (warm) focal plane mechanism offers several choices of circular translucent masks, all with flat-topped gaussian transmission profiles and central attenuations of order 0.5%. The masks effectively boost the dynamic range of the detector, allowing us to accurately determine the position and flux of the central star relative to any faint companion candidates. NICI's internal (cryogenic) pupil mechanism allows for several hard-edged stops, which help to remove PSF artifacts associated with the edges of the Gemini-South secondary mirror. Following the focal-plane mask and pupil stop, the beam is divided with a 50/50 beam-splitter into two imaging channels that are read out simultaneously.

For ages of  $\lesssim 100$  Myr, ultracool ( $T_{\text{eff}} < 1300$  K) objects with near-IR photospheric  $\text{CH}_4$  absorption correspond to masses of  $\lesssim 12 M_{\text{Jup}}$  according to evolutionary models (e.g., 9), and hence  $\text{CH}_4$  absorption is expected to be a characteristic signature of young planets. IR imaging of young planets in and out of this absorption band will produce a unique photometric signature, strong emission in the blue band and little emission in the red one, that can be distinguished from the bright (methane-free) glare of the parent star.<sup>10</sup> The SDI approach was first attempted with the Trident camera on CFHT<sup>11</sup> and has also been used for the SDI cameras on the VLT and MMT.<sup>12,13</sup> Similar to these instruments, NICI provides time simultaneous methane-band imaging in order to counteract the time-variable AO PSF. NICI implements SDI through dual-channel imaging design, with each channel being an independent optical channel with its own  $1024 \times 1024$  ALADDIN InSb detector (**Figure 2**). The spectral properties of the  $H$ -band on+off methane filters in NICI were custom designed to maximize the combination of sensitivity and accurate SDI subtraction, based on an end-to-end simulation of the expected imaging performance (see 8). The resulting filters are 4% wide, with central wavelengths of  $1.578 \mu\text{m}$  (off-methane) and  $1.652 \mu\text{m}$  (on-methane).

NICI can also employ ADI (a.k.a. roll subtraction; 14,15) to distinguish between long-lived telescope+instrument

speckles and faint astronomical objects, thereby removing the PSF and achieving higher contrast. Altogether, NICI offers a number of imaging options, through the use of ADI, SDI, or both; this versatility makes it novel compared to other previous AO instruments. For instance, dual-channel data obtained with ADI+SDI mode can also be summed, instead of differenced as in the SDI processing, to yield a pseudo-broadband ADI dataset. Likewise, the instrument can be used in single-channel ADI-only mode, where an internal mirror is used to send all the light to one detector, thereby maximizing the throughput. *NICI's versatile imaging configurations make it sensitive to very faint companions, both with and without photospheric methane absorption.*

### 3. GOALS AND STRATEGY

To take full advantage of the powerful capabilities of NICI, we are leading a three-year guaranteed-time campaign at the Gemini-South 8.1-meter Telescope dedicated to finding and characterizing planets by direct imaging. The Campaign is designed to address three key questions in the study of gas-giant extrasolar planets:

1. ***What is the frequency of outer ( $>5\text{--}10\text{ AU}$ ) massive planets around other stars?*** Determining the incidence and properties of outer planetary companions will allow us to develop a complete picture of exoplanetary configurations. To this end, one major goal of the NICI Campaign is to probe the mass and separation distribution ( $dN/dM/da$ ) of planets at distances as close as  $\gtrsim 5\text{--}10\text{ AU}$ , as inferred from the complete set of NICI detections (discoveries) and non-detections. This distribution may have profound consequences for assessing the dominant formation mechanism of gas-giant planets.
2. ***What is the dependence of planet frequency on the stellar host mass?*** The frequency of giant planets in the outer regions of low-mass stars (M dwarfs) is another key discriminant between the two competing theories of giant planet formation, namely core accretion and disk instability. By design, the Campaign is searching for planets around young stars over a wide range of masses, from spectral type B7 to M6. This is feasible thanks to the sensitivity of NICI's curvature-based AO system to optically faint stars. RV surveys find few massive planets in the inner  $\lesssim 1\text{ AU}$  regions around low-mass stars (e.g., 16, 17); the NICI Campaign will be a complementary study of the outer regions around these objects.
3. ***What are the spectrophotometric properties of young extrasolar planets?*** Follow-up multi-band photometry and spectroscopy of directly imaged planets will test theoretical models, which are far from mature. The discovery space is large and unexplored. Cooling models may be incorrect or missing key opacity sources. Indeed, one of the early surprises from RV discoveries was the diversity of exoplanet orbits. Whether this diversity extends to their spectral energy distributions (SEDs) is an important open question. Initial studies of the SEDs of the HR 8799 planets point to unusually cloudy, non-equilibrium photospheres compared to field brown dwarfs, suggesting extreme physical properties in ultracool atmospheres at young ages (1, 5, 7). However, many more systems are needed for study.

To achieve these goals, the NICI Campaign is mostly targeting nearby young ( $\lesssim 300\text{ Myr}$ ) stars, where planets are expected to be hot enough and luminous enough for direct detection at near-IR wavelengths. One added virtue of NICI is that it is deployed at Gemini-South. While numerous young stars have been recognized in the last 5–10 years all over the sky, the most promising of the currently known moving groups reside in the southern hemisphere (e.g., 19–21).

We also carried out complementary efforts to identify previously unrecognized young stars as targets prior to the start of the Campaign, focusing on low-mass stars (M dwarfs) within 25 pc.<sup>22</sup> The current young star census is mostly restricted to higher-mass (AFGK-type) stars and contains few M dwarfs. This paucity is striking, especially considering that M dwarfs dominate the stellar mass function by number: M dwarfs comprise  $\approx 70\%$  of a volume-limited census (e.g., 23). To find this “missing” population, we used X-ray activity+color selection to identify candidates and high-resolution optical spectroscopy to refine their age estimates, through gravity-sensitive indices, strong H $\alpha$ , lithium, and UVW space velocities. The vast majority of our M dwarfs are not in any previously published young star sample, illustrating the novelty of our search.

To select and prioritize targets, prior to the start of the Campaign we employed Monte Carlo simulations to evaluate the science return of different approaches: deeper vs. shallower exposures; more vs. fewer targets;

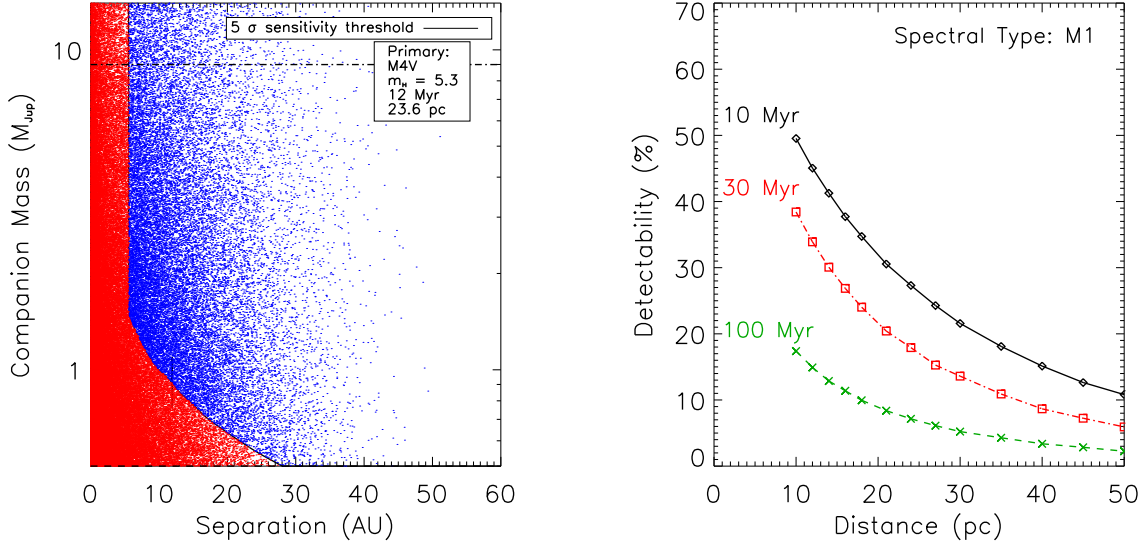


Figure 3. Illustrations of our Monte Carlo simulations for Campaign target selection and prioritization, based on the methodology of Nielsen et al. (e.g., 18). **Left:** A set of 100,000 simulated planets are shown, with blue points marking planets above the detection threshold, and red points marking planets not detected by NICI. For this particular star, 25% of simulated planets can be detected, i.e., Detectability = 25%. We carried out these detailed simulations for all stars on our initial target list. **Right:** The fraction of planets detected around an M1 primary as a function of target star distance, showing the trade-off with target age for an input planet population with a semi-major axis distribution  $dN/da \propto a^{-0.5}$  from 0.03–30 AU. The nearest, youngest stars are favored, though more nearby, slightly older stars can be better targets than younger stars farther away.

younger, more distant targets vs. older, closer targets, etc. Our approach is based on the methods developed by Nielsen et al. (e.g., 18). The ranking of targets is done by simulating a large number of planets (100,000) around each star, with planets drawn from mass, semi-major axis, and eccentricity distributions consistent with the known RV planet population and null results from previous direct imaging surveys.<sup>24</sup> The brightness, age and distance of the host star establish the apparent magnitudes, flux ratios, and projected separations of the simulated planets. The simulated planets were then compared with the expected NICI companion sensitivity to determine what fraction would be detected (**Figure 3**). This approach allows us to understand the trade-offs of the relevant factors: age, distance, host star luminosity, AO performance, exposure times, and overall sample size. The result is that the best stars can be identified for deep NICI imaging, out of thousands of possible targets. In short, the NICI Campaign has been designed to maximize the likelihood of detecting planets; as a natural consequence, this also ensures that even a null result would have profound scientific impact, strongly constraining the possible populations of long-period giant extrasolar planets.

The final Campaign target list is composed primarily of stars with ages of  $\lesssim 300$  Myr and distances of  $\lesssim 70$  pc. It does include stars with older ages or larger distances that are promising targets, especially if they have ancillary evidence for being hosts of planetary systems (e.g., the presence of circumstellar debris disks). Our simulation effort showed that the “best” list of stars depends to some degree on the assumed input planet population, especially the adopted outer orbital separation and its dependence (or lack thereof) on stellar host mass. This was not surprising, though the full extent of the effect is perhaps unappreciated in previous such simulations — the choices that go into the modeling inevitably sway the outcome. In the end, we synthesized the results from simulations with different assumptions, ensuring the broad range of spectral types needed to study the dependence of planet frequency on stellar host mass (Campaign goal #2). The final sample is split roughly equally between high-mass stars (AF spectral types), solar-type stars (GK types), and low-mass stars (M type).



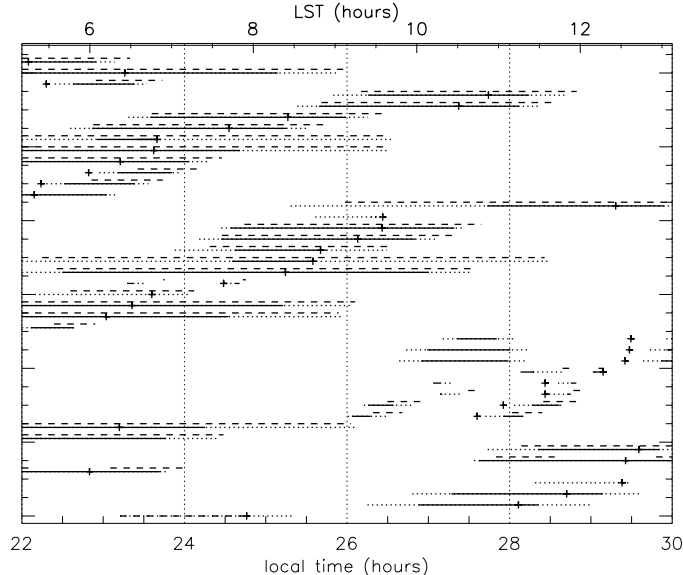


Figure 4. An example of the observing windows for a typical NICI Campaign night. Each set of dotted+dashed+solid lines represents the allowable start time for one science target, where the sky rotation is matched to our ADI requirements on the instantaneous rotation rate and the total amount of rotation for each dataset. (The different line styles corresponded to slightly different calculations.) The + sign marks the transit for each target. Each observing night is planned to optimize the target priorities, given the feasible observing windows.

#### 4. STATUS

The Campaign began science observations in December 2008, with monthly observing runs executed in fixed blocks of several nights during bright time. Observations are executed on-site by Gemini staff, with real-time remote support by Campaign team members via Polycom. Most NICI observations have been carried out during the Chilean summer, from November to April when seeing conditions are favorable for AO imaging. First-epoch observations for 178 stars have been obtained so far, more than half the Campaign goal of 300 stars.

Thanks to the extensive on-sky characterization during the commissioning phase and first year of the Campaign, we have developed a stable set of observing protocols that are now used for almost all Campaign observations,<sup>25</sup> ensuring homogenous datasets that are directly amenable to prompt pipeline processing and common science analysis. Most targets are observed contemporaneously with two instrument configurations: (1) a dual-channel ADI+SDI mode (“ASDI”) with the 4% 1.6  $\mu\text{m}$  methane on+off filters and (2) a single-channel ADI-only mode with the regular  $H$ -band filter. This “hybrid” scheme provides the greatest sensitivity over a range of separations. The ASDI mode delivers the highest contrasts in the inner  $\lesssim 1.0\text{--}1.5''$  where speckle noise dominates, while the ADI-only mode offers the greatest sensitivity to faint companions at larger separations.

Each night, we design an observing plan to carefully control the amount of sky rotation for each target (**Figure 4**). Too much instantaneous rotation during a single ADI exposure will lead to too much blurring and thus loss of point-source sensitivity at larger separations. Too little total rotation over the entire observing sequence for a target will make it difficult to construct an appropriate PSF for ADI data reduction and lead to self-subtraction at smaller separations. Fundamentally, the duration of an observing window is a function of target declination. For objects that transit close to overhead, these windows can be very brief, sometimes only 10-20 minutes long. For more northerly or southerly targets, the observing windows are longer, up to several hours in duration, and therefore easier to schedule. Given a prioritized list of science targets, we assemble a custom schedule for each night, fitting together the differently sized observing windows for all the targets. This ensures that objects with difficult (short) observing windows will be observed with an optimal rate and total amount of sky rotation.

Data processing and analysis occur immediately during and after each run, providing the feedback on data

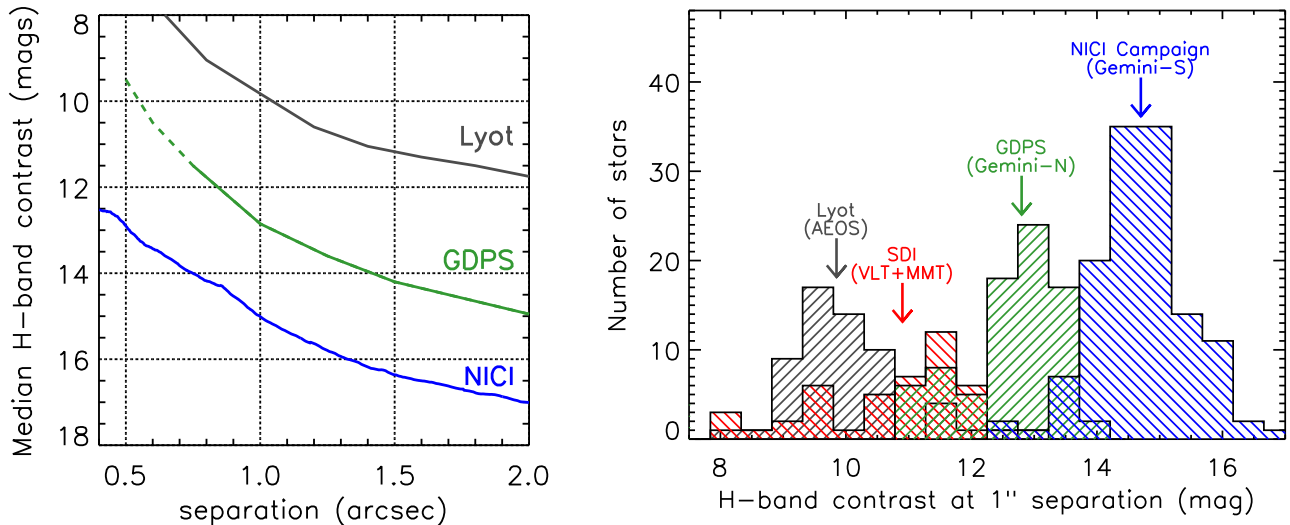


Figure 5. **Left:** The median H-band contrast curve for point-source detection from the NICI Campaign so far (typical on-source integration time of 45 min), compared to the Gemini Deep Planet Survey conducted at Gemini-North<sup>26</sup> and the Lyot Project at the AEOS Telescope.<sup>27</sup> The NICI Campaign curve merges the dual-channel ASDI data taken with the 4% methane filters and single-channel ADI datasets taken with the standard H-band filter. For GDPS, the data were obtained with a 6% methane-off ( $1.58\ \mu\text{m}$ ) filter. Also, many of the GDPS stars were saturated in the innermost regions, hence the dashed line. **Right:** Comparison of the NICI Campaign so far with the aforementioned surveys and also the VLT+MMT/SDI survey.<sup>28</sup> The plotted histogram shows the point-source detectability at  $1''$  separation for every star observed by these surveys. The NICI Campaign is not yet completed (only about 1/2 the sample has been observed), but is already the largest, most sensitive planet-imaging survey to date.

quality and any potential discoveries needed to plan the next block of observing. with the combined angular+spectral differencing imaging (ASDI) mode and the ADI-only mode. Individual images are scaled, registered, radially aligned, and optimally differenced to subtract the PSF halo and speckles from the bright star, thereby revealing any faint, close companions. The pipeline is a fully working system, has already processed  $\approx 300$  hours of Campaign observations, and has been vetted via fake-companion injection+recovery experiments. The overall contrast performance achieved by the NICI Campaign is a significant advance over previous ground-based or space-based direct imaging surveys, by at least a factor of  $\approx 2$  mag (**Figure 5**).

From first-epoch observations, the Campaign has identified many high-quality substellar candidate companions (**Figure 6**). “High-quality” here means that the candidates pass multiple selection criteria: (1) they are robust detections, far above the false positive rate in the residual speckles in processed data; (2) they occur around stars with low stellar backgrounds, as judged by an infrared galactic star count model (based on 29,30); and (3) they have a reasonable projected physical separation ( $< 200$  AU). The large number of detections is not surprising, given the extreme depth of Campaign observations.

A key part of our ongoing observing is to confirm or refute these candidates via second-epoch measurements, with the first discoveries now being confirmed (**Figure 7**). New companions, especially at the lowest masses, require stringent validation. Proper motion measurements from second-epoch NICI imaging will assess if candidates are physically associated with their primaries. Almost all of our targets have well-measured proper motions and parallaxes, needed to distinguish background stars from true companions. The Campaign pipeline delivers high quality astrometry ( $\approx 1\text{--}5$  mas) of very faint (by a factor of  $\approx 10^{5\text{--}7}$ ) point sources next to bright stars, as validated by fake-companion injection and multi-epoch measurements of dense stellar fields. An example of our astrometric performance from high contrast images is illustrated by the case of UY Pic (**Figure 8**), an AB Dor moving group member with a very faint  $0.8''$  companion that we have confirmed to be a background object.

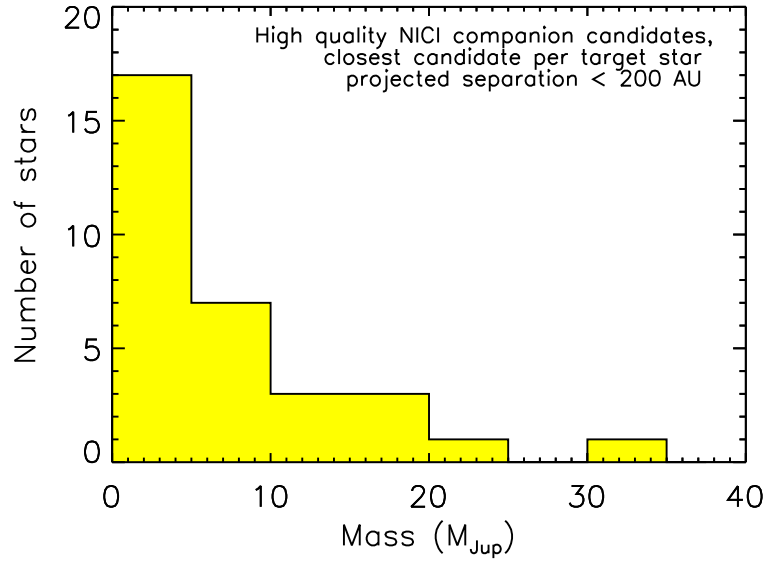


Figure 6. Histogram of high-quality companion candidates found from Campaign first-epoch observations, with masses estimated from their absolute magnitudes, the estimated ages of their host stars, and hot-start evolutionary models.<sup>9, 31</sup> The plotted data comprise only stars at high galactic latitude with candidates at  $<200$  AU separation and show only the closest candidate for each star. Most of these are expected to be uninteresting background stars, but some will be bona fide companions. Follow-up observations are currently underway.

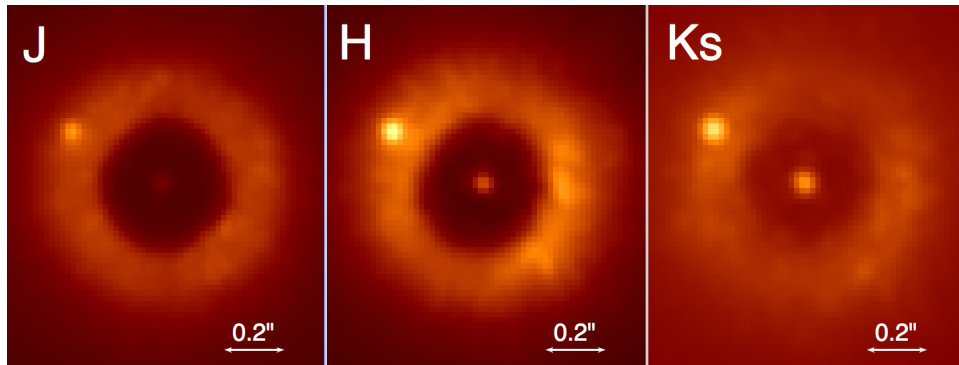


Figure 7. NICI images of a newly discovered substellar companion to the young star PZ Tel, a  $\beta$  Pic moving group member (from 32). The primary star resides at the center of the translucent focal plane mask. The companion is seen at a separation  $0.36''$  (18 AU) in the 10 o'clock position. Two epochs of NICI imaging over 13 months has confirmed this as a common proper motion companion at very high confidence. A small amount of radial orbital motion is also detected, indicating a rather eccentric orbit for the companion ( $e > 0.6$ ). The estimated mass of PZ Tel B is  $36 \pm 6 M_{\text{Jup}}$ , based on its absolute magnitudes and the Lyon/DUSTY evolutionary models. This is one of the tightest substellar companions directly imaged to date, and thus is a promising system for long-term monitoring of orbital motion.



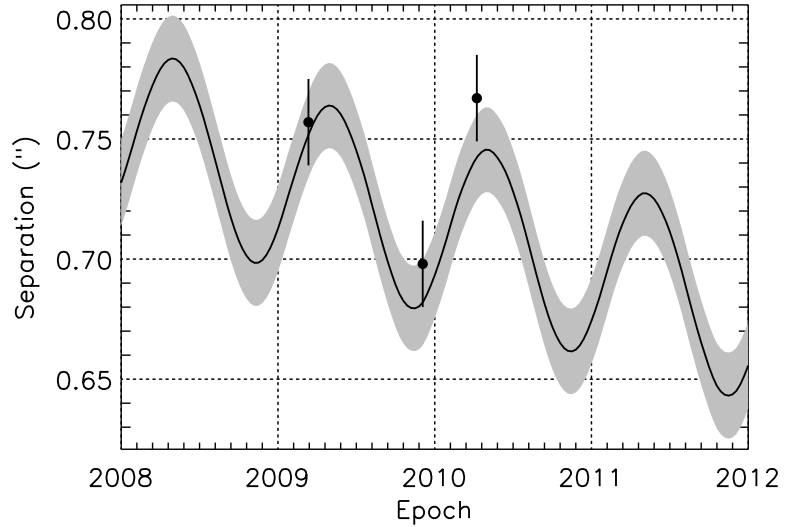
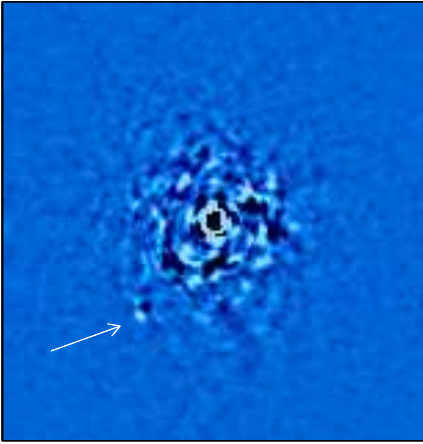


Figure 8. **Left:** A fully processed NICI 1.6  $\mu\text{m}$  ASDI dataset of the young star UY Pic, a member of the 70 Myr AB Dor moving group. The halo of the bright primary star has been removed by the Campaign pipeline. The FOV of this cutout is 2.7'' on a side. (The full NICI FOV is 18.4''.) The arrow points to a very faint non-methanated companion, which has a positive/negative dipole appearance due to the SDI subtraction process. The companion has a projected separation of 0.8'' and is 12.1 magnitudes fainter than the primary star. If physically associated, it would have had a mass of 7  $M_{\text{Jup}}$  and a physical separation of 19 AU. **Right:** Three epochs of NICI astrometry of the faint companion, shown as the black points with error bars. The tilted sinusoidal curve shows the expected separation of the companion if it were a background object at infinite distance, given the known parallax and proper motion of the primary star and the first-epoch astrometric uncertainties. The candidate is shown clearly to be a background object. (In this case, three epochs of data were taken to eliminate the possibility that orbital motion of the companion would confuse an analysis based on two epochs of data alone.)

## 5. PROGNOSIS

The Campaign is planned to continue for three more semesters, through the end of 2011. Overall, the Campaign is about halfway done, in terms of first-epoch observing of the target list. In addition, we are now transitioning into a new phase, namely the confirmation of new companions. Astrometric and photometric followup of new discoveries can be done with NICI alone, as illustrated above. Spectroscopic followup of the brighter discoveries is feasible with current AO integral-field spectrographs, as demonstrated by the high-contrast data that have been obtained with VLT/SINFONI and Keck/OSIRIS (e.g., 7, 33). Companions confirmed at the faintest limits of NICI will be beyond current spectroscopic capabilities, and analysis will be restricted to photometry alone; however, such objects will be ideal for detailed studies with next-generation planet-hunting instruments such as Gemini/GPI and VLT/SPHERE. In addition, the first-epoch astrometry from NICI discoveries will be a unique historical resource, which has motivated our efforts to deliver the highest quality measurements. Determining the orbital properties of directly imaged planets is a highly desired long-term goal in this field.

While still in progress, the NICI Planet-Finding Campaign already represents the largest and most sensitive imaging survey to date for massive ( $\gtrsim 1 M_{\text{Jup}}$ ) planets around other stars. The same Monte Carlo simulation methods used for the original Campaign planning are currently being adapted for a uniform analysis of the Campaign detections (new companions) and non-detections simultaneously, in order to precisely determine the gas-giant exoplanet mass and separation distribution. By virtue of its unprecedented sample size, depth, and uniformity, the Campaign will establish the best measurements to date on the properties of gas-giant planets at  $\gtrsim 5\text{--}10$  AU separations.

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